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THE GZK FEATURE IN THE SPECTRUM OF ULTRA HIGH ENERGY COSMIC RAYS

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ABSTRACT

The detection of the GZK feature in the cosmic ray spectrum, resulting from the production of pions by ultra-high energy protons scattering off the cosmic microwave background (CMB), can shed light on the mysterious sources of these high energy particles. Using numerical simulations we developed for the propagation of Ultra High Energy Cosmic Rays (UHECR) in the CMB we determine the statistical significance of the GZK feature in the spectrum of UHECR measured by AGASA and HiRes and we show that, with the small sample of events with energies $\sim 10^{20}$ eV detected thus far, an accurate and statistically significant determination of the GZK feature is not possible. The data from these two experiments are best fit by two different injection spectra in the region below 10^{20} eV, and a comparison of the spectra suggests the presence of about a 30% systematic errors in the relative energy determination. Correcting for these systematics, the two experiments are best fit by the same injection spectrum in the region below 10^{20} eV, while above this threshold they maintain their disagreement, but only at the 2σ level. These results

clearly show the need for much larger experiments such as Auger, EUSO and OWL, that can increase the number of detected events by one or two orders of magnitude making the determination of the GZK feature feasible.

1 Introduction

Astrophysical proton sources distributed homogeneously in the universe produce a feature in the energy spectrum due to the production of pions off the CMB. This feature, consisting of a rather sharp suppression of the flux, occurs at energies above $E_{\text{GZK}} \sim 7 \times 10^{19}$ eV, and it is now known as the GZK cutoff. Almost forty years after this prediction it is not yet clear if this effect is observed or not due to the discrepancy between the results of the two largest experiments measuring the spectrum of Ultra High Energy Cosmic Rays (UHECRs). AGASA ¹⁾ reports a higher number of events above E_{GZK} than expected while HiRes ²⁾ reports a flux consistent with the GZK feature. Here we report on a detailed investigation ³⁾ of the statistical significance of this discrepancy as well as the significance of the presence or absence of the GZK feature in the data. We find that neither experiment has the necessary statistics to establish if the spectrum of UHECRs has a GZK feature. In addition, a systematic error in the energy determination of the two experiments seems to be required in order to make the two sets of observations compatible in the low energy range, $10^{18.5} - 10^{19.6}$ eV, where enough events have been detected to make the measurements reliable. Taking into account the systematics, the two experiments predict compatible fluxes at energies below E_{GZK} and at energies above E_{GZK} the fluxes are within $\sim 2\sigma$ of each other.

The detection or non-detection of the GZK feature in the cosmic ray spectrum remains open to investigation by future generation experiments, such as the Pierre Auger project and the EUSO and OWL experiments.

The paper is organized as follows: in § 2 we briefly describe the simulations used to propagate cosmic rays, in § 3 we illustrate the present observational situation, limiting ourselves to AGASA and HiResI, and compare the data to the predictions of our simulations. We conclude in § 4.

2 Cosmic Rays Propagation

We assume that UHECRs are protons injected in extragalactic sources with a power-law spectrum with slope γ and an exponential cutoff at $E_{\max} = 10^{21.5}$ eV, large enough not to affect the statistics at much lower energies. Based on the results of ⁴⁾ we assume a spatially uniform distribution of sources and do not take into account luminosity evolution in order to avoid the introduction of additional parameters. We simulate the propagation of protons from source to observer by including the photo-pion production, pair production, and adiabatic energy losses due to the expansion of the universe. In each step of the simulation, we calculate the pair production losses using the continuous energy loss approximation given the small inelasticity in pair production ($2m_e/m_p \simeq 10^{-3}$). For the rate of energy loss due to pair production at redshift $z = 0$, $\beta_{\text{pp}}(E, z = 0)$, we use the results from ^{5, 6)}. At a given redshift $z > 0$,

$$\beta_{\text{pp}}(E, z) = (1 + z)^3 \beta_{\text{pp}}((1 + z)E, z = 0). \quad (1)$$

Similarly, the rate of adiabatic energy losses due to redshift is calculated in each step using

$$\beta_{\text{rsh}}(E, z) = H_0 [\Omega_M(1 + z)^3 + \Omega_\Lambda]^{1/2} \quad (2)$$

with $H_0 = 75 \text{ km s}^{-1}\text{Mpc}^{-1}$.

The photo-pion production is simulated in a way similar to that described in ref. ⁴⁾. In each step, we first calculate the average number of photons able to interact via photo-pion production through the expression:

$$\langle N_{\text{ph}}(E, \Delta s) \rangle = \frac{\Delta s}{l(E, z)}, \quad (3)$$

where $l(E, z)$ is the interaction length for photo-pion production of a proton with energy E at redshift z and Δs is a step size, chosen to be much smaller than the interaction length (typically we choose $\Delta s = 100 \text{ kpc}/(1 + z)^3$).

We then sample a Poisson distribution with mean $\langle N_{\text{ph}}(E, \Delta s) \rangle$, to determine the actual number of photons encountered during the step Δs . When a photo-pion interaction occurs, the energy ϵ of the photon is extracted from the Planck distribution, $n_{\text{ph}}(\epsilon, T(z))$, with temperature $T(z) = T_0(1 + z)$, where $T_0 = 2.728 \text{ K}$ is the temperature of the cosmic microwave background at

present. Since the microwave photons are isotropically distributed, the interaction angle, θ , between the proton and the photon is sampled randomly from a distribution which is flat in $\mu = \cos\theta$. Clearly only the values of ϵ and θ that generate a center of mass energy above the threshold for pion production are considered. The energy of the proton in the final state is calculated at each interaction from kinematics. The simulation is carried out until the statistics of events detected above some energy reproduces the experimental numbers. By normalizing the simulated flux by the number of events above an energy where experiments have high statistics, we can then ask what are the fluctuations in numbers of events above a higher energy where experimental results are sparse. The fits are therefore most sensitive to the energy regions below E_{GZK} and give a good estimate of the uncertainties in the present experiments for energies above E_{GZK} . In this way we have a direct handle on the fluctuations that can be expected in the observed flux due to the stochastic nature of photo-pion production and to cosmic variance.

The simulation proceeds in the following way: a source distance is generated at random from a uniform distribution in a universe with $\Omega_\Lambda = 0.7$ and $\Omega_m = 0.3$, a particle energy is assigned from a distribution that reflects the injection spectrum then this particle is propagated to the observer and its energy recorded. This procedure is repeated until the number of events above a threshold energy, E_{th} is reproduced. With this procedure we can assess the significance of results from present experiments with limited statistics of events. There is an additional complication in that the aperture of the experiment usually depends on energy. This is taken into account by allowing the event to be detected or not depending upon the function $H(E)$ that describes the energy dependence of the aperture.

We only study the spectrum above $10^{18.5}$ eV where the flux is supposed to be dominated by extragalactic sources. For this energy range, we focus on the experiments that have the best statistics: AGASA and HiResI. For AGASA data, the simulation is stopped when the number of events above $E_{th} = 10^{19}$ eV equals 866. For HiRes this number is 300. The statistical error in the energy determination is accounted for in our simulation by generating a *detection* energy chosen at random from a Gaussian distribution centered at the arrival energy E and with width $\Delta E/E = 30\%$ for both experiments.

Our simulations reproduce well the predictions of analytical calculations,

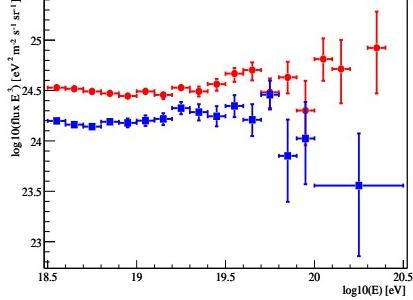


Figure 1: Circles show the AGASA spectrum while squares show the HiResI spectrum.

in particular at the energies where energy losses may be approximated as continuous (see ³⁾ for a detailed comparison).

3 AGASA versus HiResI

The two largest experiments that measured the flux of UHECRs report apparently conflicting results. The data of AGASA and HiResI on the flux of UHECRs multiplied as usual by the third power of the energy are plotted in Fig. 1 (the squares are the HiResI data while the circles are the AGASA data). The figure shows that HiResI data are systematically below AGASA data and that HiResI sees a suppression at $\sim 10^{20}$ eV that resembles the GZK feature while AGASA does not.

We apply our simulations here to the statistics of events of both AGASA and HiResI in order to understand whether the discrepancy is statistically significant and whether the GZK feature has indeed been detected in the cosmic ray spectrum. In order to understand the difference, if any, between AGASA and HiRes data we first determine the injection spectrum required to best fit the observations. The injection spectrum is taken to be a power law with index γ between 2.3 and 2.9 with steps of 0.1. For each injection spectrum we calculated the χ^2 indicator (averaged over 400 realizations for each injection spectrum). The errors used for the evaluation of the χ^2 are due to the square roots of the number of observed events. It is important to note that the fits are dominated by the low energy data rather than by the poorer statistics at

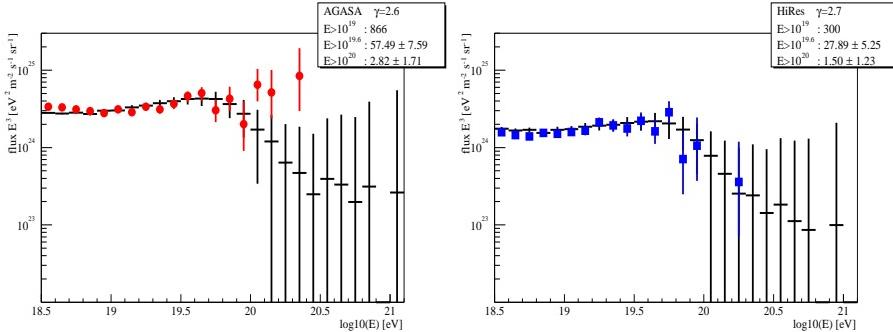


Figure 2: *Simulations of AGASA and HiRes statistics. crosses with error bars: simulations, grey points: experimental data.*

the higher energies.

If the data at energies above $10^{18.5}$ eV are taken into account for both experiments, the best fit spectra are $E^{-2.8}$ for AGASA and $E^{-2.6}$ for HiRes. If the data at energies above 10^{19} eV are used for the fit, the best fit injection spectrum is $E^{-2.6}$ for AGASA and between $E^{-2.7}$ and $E^{-2.8}$ for HiRes. If the fit is carried out on the highest energy data ($E > 10^{19.6}$ eV), AGASA prefers an injection spectrum between $E^{-2.5}$ and $E^{-2.6}$, while $E^{-2.8}$ or $E^{-2.9}$ fit better the HiRes data in the same energy region. Note that the two sets of data uncorrected for any possible systematic errors require different injection spectra that change with E_{th} .

In order to quantify the significance of the detection or lack of the GZK flux suppression, we calculate the mean number of events above two energy thresholds ($10^{19.6}$ eV and 10^{20} eV), $\langle N(E > E_{th}) \rangle$, for different injection spectra and compare them to the experimental results. We find that while HiResI is consistent with the existence of the GZK feature in the spectrum of UHE-CRs, AGASA detects an increase in flux, but only at the $\sim 2.1\sigma_{tot}$ level. Here $\sigma_{tot} = (\sigma_{sim}^2 + \sigma_{obs}^2)^{1/2}$ is the combined uncertainty from simulations and observed data.

A more graphical representation of the uncertainties involved are displayed in Fig. 2. These plots show clearly the low level of significance that the detections above E_{GZK} have with low statistics. The large error bars that are generated by our simulations at the high energy end of the spectrum are mainly due to the stochastic nature of the process of photo-pion production:

in some realizations some energy bins are populated by a few events, while in others the few particles in the same energy bin do not produce a pion and get to the observer unaffected. The large fluctuations are unavoidable with the extremely small statistics available with present experiments. On the other hand, the error bars at lower energies are minuscule, so that the two data sets (AGASA and HiResI) cannot be considered to be two different realizations of the same phenomenon. Instead, systematic errors in at least one if not both experiments are needed to explain the discrepancies at lower energies.

As seen in Fig. 1, the difference between the AGASA and HiResI spectra is not only in the presence or absence of the GZK feature: the two spectra, when multiplied by E^3 , are systematically shifted by about a factor of two. This shift suggests that there may be a systematic error either in the energy or the flux determination of at least one of the two experiments. Possible systematic effects have been discussed in ⁷⁾ for the AGASA collaboration and in ⁸⁾ for HiResI. A systematic error of $\sim 15\%$ in the energy determination is well within the limits that are allowed by the analysis of systematic errors carried out by both collaborations.

In order to illustrate the difficulty in determining the existence of the GZK feature in the observed data in the presence of systematic errors, we split the energy gap by assuming that the energies as determined by the AGASA collaboration are overestimated by 15%, while the HiRes energies are underestimated by the same factor. In this case the total number of events above 10^{19} eV is reduced for AGASA from 866 to 651, while for HiResI it is enhanced from 300 to 367. We ran our simulations with these new numbers of events and repeat the statistical analysis described above.

For AGASA, the best fit injection spectrum is now between $E^{-2.5}$ and $E^{-2.6}$ above 10^{19} eV and above $10^{19.6}$ eV. For the HiRes data, the best fit injection spectrum is $E^{-2.6}$ for the whole set of data, independent of the threshold. It is interesting to note that the best fit injection spectrum appears much more stable after the correction of the 15% systematics has been carried out. Moreover, the best fit injection spectra as derived for each experiment independently coincides for the corrected data unlike the uncorrected case. This suggests that combined systematic errors in the energy determination at the $\sim 30\%$ level may in fact be present.

As above in order to quantify the significance of the detection or lack

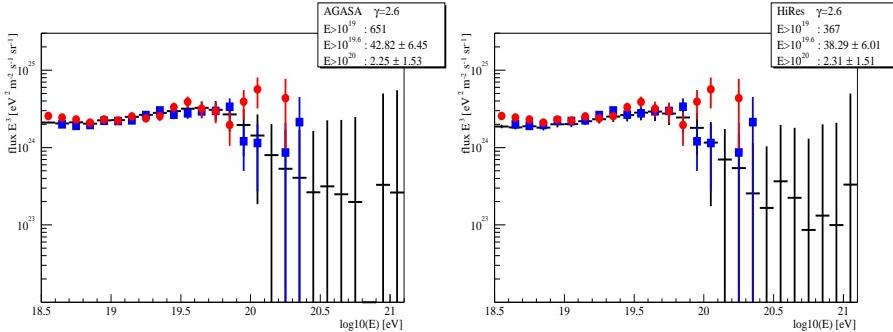


Figure 3: Simulated spectra for the best fit injection spectrum with $\gamma = 2.6$. Left panel shows simulations for the AGASA event statistics after correcting for energy by an overall shift of -15% . The right panel shows the fluctuations expected for the event statistics of HiResI after shifting HiResI energies by $+15\%$. The shifted data for AGASA (grey circles) and HiResI (dark squares) are shown in both panels.

of the GZK flux suppression, we calculate the mean number of events above two energy thresholds ($10^{19.6}$ eV and 10^{20} eV), $\langle N(E > E_{th}) \rangle$, for different injection spectra and compare them to the experimental results. We find that HiResI continues to be consistent with the existence of the GZK feature, while the discrepancy of the AGASA data is reduced at the level of $1.5\sigma_{\text{tot}}$.

In Fig. 3, we plot the simulated spectra for injection spectrum $E^{-2.6}$ and compare them to the corrected data of AGASA (left plot) and HiResI (right plot).

4 Conclusions

We considered the statistical significance of the UHECR spectra measured by the two largest experiments in operation, AGASA and HiRes. The spectrum released by the HiResI collaboration seems to suggest the presence of a GZK feature. This has generated claims that the GZK cutoff has been detected, reinforced by data from older experiments ⁹⁾. However, no evidence for such a feature has been found in the AGASA experiment. We compared the data with theoretical predictions for the propagation of UHECRs on cosmological distances with the help of numerical simulations. We find that the very low statistics of the presently available data hinders any statistically significant

claim for either detection or the lack of the GZK feature.

A comparison of the spectra obtained from AGASA and HiResI shows a systematic shift of the two data sets, which may be interpreted as a systematic error in the relative energy determination of about 30%. If no correction for this systematic shift is carried out, the AGASA and HiResI data sets are best fit by two different injection spectra that depend on the threshold used for the fit. With the best fits to the injection spectrum the AGASA data depart from the prediction of a GZK feature by 2.3σ for $\gamma = 2.6$. The HiRes data are fully compatible with the prediction of a GZK feature in the cosmic ray spectrum. It is clear that, if confirmed by future experiments with much larger statistics, the increase in flux relative to the GZK prediction hinted by AGASA would be of great interest. This may signal the presence of a new component at the highest energies that compensates for the expected suppression due to photo-pion production, or the effect of new physics in particle interactions (for instance the violation of Lorentz invariance or new neutrino interactions).

Identifying the cause of the systematic energy and/or flux shift between the AGASA and the HiRes spectra is crucial for understanding the nature of UHECRs. This discrepancy has stimulated a number of efforts to search for the source of these systematic errors including the construction of hybrid detectors, such as Auger, that utilize both ground arrays and fluorescence detectors. A possible overestimate of the AGASA energies by 15% and a corresponding underestimate of the HiRes energies by the same amount would in fact bring the two data sets in agreement in the region of energies below 10^{20} eV. In this case both experiments are consistent with a GZK feature with large error bars. The AGASA excess is at the level of 1.5σ . Interestingly enough, the correction by 15% in the error determination implies that the best fit injection spectrum becomes basically the same for both experiments ($E^{-2.6}$).

With the low statistical significance of either the excess flux seen by AGASA or the discrepancies between AGASA and HiResI, it is inaccurate to claim either the detection of the GZK feature or the extension of the UHECR spectrum beyond E_{GZK} at this point in time. A new generation of experiments is needed to finally give a clear answer to this question. In Fig. 4 we report the simulated spectra that should be achieved in 3 years of operation of Auger (left panel) and EUSO (right panel). The error bars reflect the fluctuations expected in these high statistics experiments for the case of injection spectrum

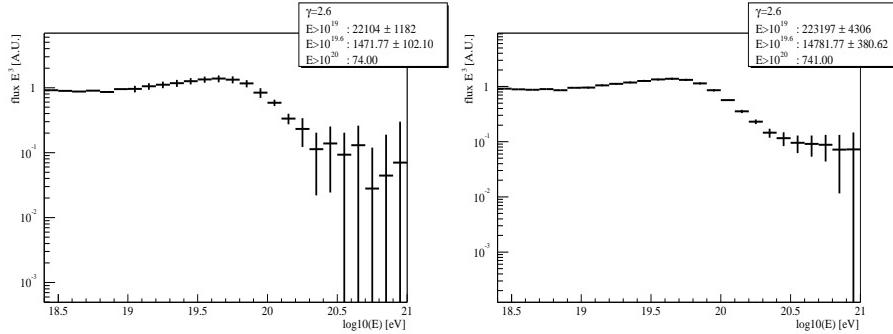


Figure 4: *Predicted spectra and error bars for 3 years of operation of Auger (left plot) and EUSO (right plot).*

$E^{-2.6}$. (Note that the energy threshold for detection by EUSO is not yet clear). It is clear that the energy region where statistical fluctuations dominate the spectrum is moved to $\sim 10^{20.6}$ eV for Auger, allowing a clear identification of the GZK feature. The *fluctuations* dominated region stands beyond 10^{21} eV for EUSO.

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